The Deep Impact Mission and the AAVSO

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Abstract NASA's eighth Discovery mission, Deep Impact, will arrive at comet 9P/Tempel 1 in July 2005. The spacecraft will deliver a 370-kg impactor to the comet to excavate a large crater. The science goals will be (a) to excavate down to unaltered material to learn about the chemical and physical conditions in the early solar system and (b) to learn about cratering processes in small bodies and the mechanical properties of the cometary surface layers. In addition to optical imaging and near-IR imaging on the spacecraft, there will be a world-wide network of professional ground-based and space-based telescopes observing the event. A large role for mission support from observers with small telescopes will be discussed in this paper.

1. Introduction

In 2004 NASA will launch the Deep Impact Mission with the goal of exploring the interior of the nucleus of comet 9P/Tempel 1. On July 3, 2005, a 370-kg impactor will be released from the Deep Impact spacecraft, colliding with the comet 24 hours later at 10.2 km/s. Within a few hundred seconds the impactor will excavate a crater possibly equivalent in size to a football field and several stories deep, while the flyby spacecraft takes imaging and spectroscopic data.

Comets are primordial remnants of the solar system's origin whose surfaces are probably significantly evolved since formation. In order to understand the chemical and physical clues from the early solar system that comets may provide, samples of pristine matter are necessary. The Deep Impact Mission impactor reaches down to this pristine material. The mission will involve space-based, earth-orbital, and ground-based data collection, and we are planning to involve a large network of small telescopes to help support the mission. The AAVSO observers comprise a valuable resource for mission support.

Historically, comets have inspired terror because of their sudden appearance, potentially great brightness, and large tails. Early spectra also identified the presence of toxic chemicals and this helped contribute to their sometimes unpopular reputations. However, modern astronomers are excited about comet observations because of the information they preserve about the early solar system.

Comet nuclei represent the icy planetesimals which were left over from the collapse of the solar nebula. They probably formed in the vicinity of the giant planets outwards to the Kuiper Belt, beyond Pluto. It is likely that most of the original interstellar grains were altered as this material fell through the shocks in the midplane of the solar nebula. Models show that much of the icy components of the grains would have vaporized, and then quickly recondensed on the refractory grain cores. The nebular temperatures would have been a steep function of distance from the central protosun. Laboratory experiments show that water ice condensing at temperatures below 100K will form in an amorphous phase and trap large amounts of other volatile materials in the water ice matrix. The amount of trapping is very sensitive to the condensation temperature. Small icy planetesimals then grew from this material.

The rate of growth and scattering of the planet embryos as a function of heliocentric distance depended on the size and mass distribution of the km-sized planetesimals, their surface density in the nebula, and their velocity distributions (Lissauer and Stewart 1993). The larger bodies probably formed by collisions from a narrow range of cometesimal sizes (10s to 100s of meters) (Weidenschilling 1997). Because of collisions and growth timescales, planetesimals may have migrated to different heliocentric distances. This allowed planetesimals of different chemical compositions to be incorporated into single bodies.

While we cannot directly observe this formation process during the first few million years of our solar system's history, today's comets and Kuiper belt objects have preserved a record of the outer nebula mass distribution, collisional evolution, and chemical composition. Thus, these archaeological remnants have the potential to give us access to this poorly understood planetesimal stage of evolution through observations of today's comets and Kuiper belt objects. However, to interpret observations of modern comets and learn about the early history, we need to understand the difference between cometary material which has been substantially altered since that time and that which is "fresh."

1.1. Summary of Comet Missions

We have in-situ data points for only two comet nuclei at present, 1P/Halley and 19P/Borrelly (see Figure 1). Both nuclei are irregularly shaped bodies with extremely low albedos. Both exhibit significant topographic features, and the high resolution images reveal very localized sources of activity (jets). We only have information about their surface properties; their interiors remain a mystery. Thus our existing in-situ data don't sample the early solar system.

The current suite of comet missions planned (see Table 1) is a comprehensive reconnaissance of the surfaces of comets, but only one mission, Deep Impact, explores the relationship between the pristine interior and the surface. The mission will involve space-based, earth-orbital, and ground-based data collection, and we are planning to involve a large network of small telescopes to help support the mission. The AAVSO observers comprise a valuable resource for mission support.

2. The Deep Impact Mission

The Deep Impact mission is the eighth Discovery mission. It will be the first experiment to probe beneath the surface of a comet to study the pristine interior material—initiating a new dimension in the study of cometary nuclei.

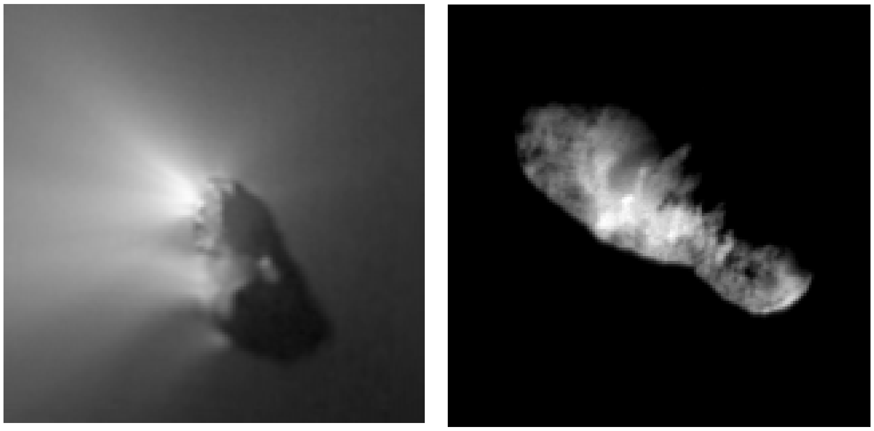

Figure 1. *Left:* Nucleus of comet 1P/Halley at 50m resolution from the Giotto spacecraft 5 min before closest approach. The nucleus size is 15.3X7.2X7.2 km. Credit: MPAE. *Right:* Deep Space 1 image of comet 19P/Borrelly from a distance of 3417 km with a resolution of 45m per pixel. The nucleus length is ~8 km. Credit: NASA/JPL.

Table 1. Current Comet Missions

Mission	*Launch*	*Enc*	*Target*	*Comments*
Deep Space 1	10/98	09/01	19P/Borrelly	Flyby
Stardust	02/99	01/04	81P/Wild 2	Sample
CONTOUR	07/02	11/03	2P/Encke	Lost
Deep Impact	01/04	07/05	9P/Tempel 1	Impact
Rosetta	TBD*	TBD*	TBD*	Orbiter

**To be determined: Postponed 1/14/2003 due to Arianne launch vehicle problems; see http://sci.esa/int/home/rosetta/index.cfm for press releases.*

Launch will occur in early 2004 January using a Delta II rocket, and the spacecraft will swing by Earth in 2004 December. The 370-kg impactor will be released on 2005 July 3 when the spacecraft is about 24 hours from closest approach. The flyby spacecraft will then slow down to fall behind by the time of impact. This delay will give the flyby spacecraft about 800 sec to view the impact, the ejecta, and the crater before the flyby at 500 km closest approach. The impactor will hit the comet nucleus at a velocity of 10.2 km/s, excavating a large crater as in a meteoritic impact. At the time of encounter, the spacecraft will be at a heliocentric distance, r, of 1.495 AU and a geocentric distance, Δ, of 0.905 AU.

Our primary goals are to determine the basic properties of a cometary nucleus and interior and to understand how comets evolve. We will also determine the composition of primordial ices in comets by looking beneath the surface. Secondary goals are understanding the physics of impact cratering and mechanical properties of the comet that will contribute to assessing the comet impact hazard.The properties of the crater will be sensitive to the unknown properties of the cometary nucleus, but for a particular, plausible model of the nucleus, the crater will be >100 m in diameter and >25 m deep, taking approximately 200 seconds to grow to this size.

The size of the crater will be sensitive to the comet's properties. The mission team expects that the growth of the impact crater will be controlled by the comet nucleus gravity. In this case, the final crater size is sensitive to the impactor mass, $M^{1/3}$. If instead, the crater growth is dominated by the strength of the surface materials, then the crater size will depend on the impactor density. This will result in a smaller crater with a greater depth/diameter ratio, and the details will be insensitive to the shape of the impactor. If the comet is very porous, the crater diameter could grow as large as 250 m, but with a smaller depth (~15 m). Observations of the crater growth will tell us about the comet surface properties.

3. Ground-based Observations

Prior to the encounter, the science team will conduct a vigorous program of ground- and space-based observing to characterize the nucleus of 9P/Tempel 1. The comet was discovered on April 3, 1867, and observed in 1873 and 1879, but was then lost until 1967 because a close Jupiter passage in 1881 increased its perihelion distance, making the object fainter. Dynamically, the comet appears to be a typical Jupiter-family short-period comet (P = 5.5 yr), which has probably spent considerable time in the inner solar system (~ 3×10^5 yr; Levison and Duncan 1998). Thus, we expect that the surface layers will be highly evolved by exposure to solar insolation. The level of activity of the comet appears to have been fairly stable since the 1960s (Kresák and Kresáková 1989).

The goals of the pre-impact observations include the following:

- Nucleus size and Albedo—Optical and infrared observations are used to determine the nucleus size and the albedo, or nucleus brightness. The size and mass are important for understanding the cratering physics, and for targeting and the imaging sequences.

- Nucleus Rotation—This important parameter, the rotation period and spin state, is important for developing the flyby imaging sequences and targeting. We need to be able to image the crater after it forms, without it rotating out of the field of view.

- Dust Coma Development—We determine when the comet first becomes active by looking at a brightness increase above that expected from the changing comet-sun-earth geometry as the comet approaches the sun (Figure 2). The onset of activity and the development of the dust coma give us an important baseline of activity before the impact. The shape of the comet's dust coma can also be modelled to give information about grain ejection velocities and grain size distributions, and allow us to assess the dust hazard from impacts to the spacecraft (Farnham 1996).

- Volatile outgassing—We will monitor the volatile species sublimating from the nucleus using spectroscopy to obtain information about the chemical composition of the nucleus.

The large telescope observations have acquired nearly 200 nights of data on moderate to large telescopes (2.1-m to 10-m) since 1997, focussing primarily on the determination of the rotation state. Simultaneous optical and IR data have been used to determine the nucleus has a radius of $R_N = 3.1$ km and is very dark (Fernández *et al.* 2002). The analysis of the rotation period is ongoing, but the comet rotates slowly with a period near 42 hours.

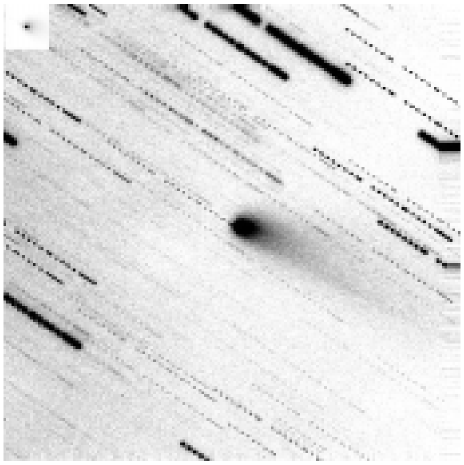

Figure 2. Composite *R*-band image of 9P/Tempel 1 from a night's worth of data taken with the UH2.2-m telescope on 2000 August 21 when the comet was 2.54 AU from the sun and 1.67 AU from the Earth (231 days post-perihelion). The field of view of the image is 7.5 arcmin on a side, and the tail extends beyond 4 arcmin ($>3 \times 10^5$ km at the distance of the comet). The inset shows the region near the nucleus and the absence of any jets. The comet's magnitude within a 5.″0 radius aperture was $R = 16.8$.

4. The Small Telescope Science Program

Professional observers have limited access to large telescopes for mission support, yet there are classes of observations needed which require long-term coverage of the comet. These are well suited for observers with small telescopes. In particular, these telescopes play an important role in monitoring the development of the dust coma, providing a large field of view to model the shape of the coma, and searching for structures in the coma. The small telescope data will also help toward understanding the rotation state of the comet nucleus.

To fulfill this need for mission science, a professional-amateur collaboration has been established: the Small Telescope Science Program (STSP), coordinated by

S. McLaughlin (stefmcl@astro.umd.edu; website: http://deepimpact.umd.edu/stsp). The program was initiated during 2000 February just after perihelion passage during this past apparition, and consists of over 40 observers from all over the world (McLaughlin *et al.* 2002).

Program data are collected in concentrated observing campaigns. The first campaign, ending in March 2001, collected over 1100 CCD images and the reductions will be complete early in 2003. The next campaign will begin during December 2003 and continue until 2006. The equipment requirements for STSP participation include a telescope with an aperture larger than 24 cm (9.5 inches), a CCD camera with a pixel resolution greater than 2 arcsec, and standard *R* and *I* filters (Kron-Cousins, Johnson, or Bessel).

The maximum brightness at perihelion is typically a visual magnitude of 9 (Kronk 1984). However, because of a large increase in the scattered light after impact from the escaping dust, predictions indicate that it could possibly reach unaided-eye brightness. Figure 3 is a plot of visual photometry versus days from perihelion, showing that the brightness is asymmetric about perihelion, peaking slightly before. Figure 4 shows this same figure, expanded in time, to include the professional data (Meech *et al.* 2000; Meech in preparation) from the 2000 apparition. This figure clearly shows the need for data from both the professional and amateur groups. During this past apparition, the STSP observers were able to monitor the comet to roughly 1 year past perihelion when the comet was near magnitude 20.

This comet is not generally known for outburst activity, however, without continuous coverage such as that which can be provided by the STSP, there are simply not enough data to rule out the possibility. Cometary outbursts can last for a few hours or months, as in the case of 2060 Chiron. We therefore invite the participation of the AAVSO membership to contribute "variable comet" observations to the STSP program. Comet orbital elements may be found at http://neo.jpl.nasa.gov/cgi-bin/db?name=9P, or, observers can obtain an ephemeris and elements from the JPL Solar System Dynamics website: http://ssd.jpl.nasa.gov/. Click on Ephemerides, WWW, and fill out the information requested for: Target Body (9P), Observer Location, Time Span, Output Quantities and Format.

5. Acknowledgements

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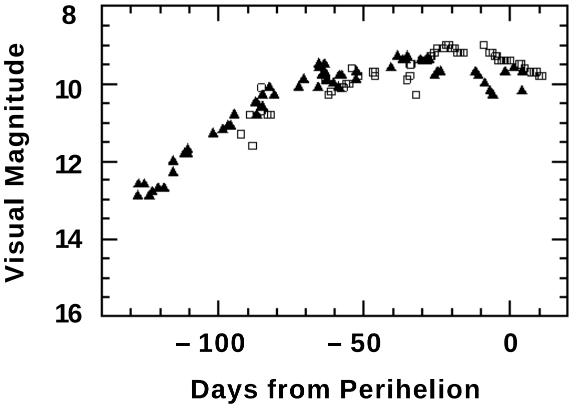

Figure 3. 9P/Tempel 1 visual photometry from selected observers—taken from the *International Comet Quarterly* (ICQ) for the apparitions 1983 (triangles; observers J. E. Bortle and J. C. Merlin) and 1994 (squares; observers D. Shanklin and J. Aguár). The data are plotted as a function of time from perihelion.

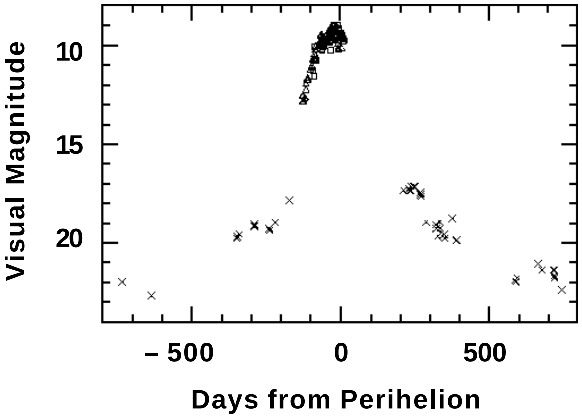

Figure 4. Plot of data from the University of Hawaii 2.2-m telescope for the 2000 apparition (crosses) in comparison to the ICQ data from Figure 3. Data were obtained by the author through a 5.″0 aperture with a Kron-Cousins *R* filter and corrected to the *V* filter using *V*-*R* = 0.45 mag.